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THE BENEFITS OF FUNCTIONAL GROUND TESTING, A CASE STUDY OF THE TOMAHAWK MISSILE FGT PROGRAM

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Abstract

The Tomahawk Functional Ground Test (FGT) Facility at the Naval Surface Warfare Center/Indian Head Division (NSWC/IHD) presents the Tomahawk program with a unique flight test risk reduction capability. The Tomahawk-Missile-in-the-Loop (TMIL) system integrates an actual strapped-down Tomahawk missile with a real time 6 DOF simulation and "flies" the missile through a mission to provide an economical means of obtaining data that could otherwise be only obtained through flight testing. A study of Tomahawk flight test failures shows that 72% of these failures could have been detected through FGT. Current estimates of the cost avoidance to the Tomahawk program resulting from FGT exceeds \$100 million. A similar capability could prove useful on other missile programs, helping to reduce flight test risk and overall test costs.

Introduction

We live in an era replete with defense challenges. The collapse of the Soviet Union and the end of the Cold War has helped to create substantial political pressure to reduce defense spending. At the same time the threat to the United States is evolving and expanding to include rogue nations who are quickly acquiring new means of attack, such as ballistic missile development. According to the Report of the Commission to Assess the Ballistic Missile Threat to the United States led by Donald Rumsfeld[1], a hostile nation could have the ability to inflict "major destruction" on the US within five years of a decision to acquire a ballistic missile capability. We face the familiar challenge of developing advanced defense systems cheaply and quickly.

A response to the technical, schedule, and budgetary challenges of Ballistic Missile Defense has been to compress flight test schedules and forgo many of the risk reducing Hardware-In-The-Loop (HWIL) and ground tests. This philosophy has been characterized in the Report of the Panel on Reducing Risk in Ballistic Missile Defense Flight Test Programs led by Gen. Larry Welch (Ret.)[2] as a "rush to failure". The study group concluded that this test philosophy would not accelerate fielded capability but would more likely lead to development delays and higher program costs. One of their major recommendations was to slow the pace of flight testing and increase the amount of high-fidelity end-to-end ground testing and simulations. Ground testing and simulations are most effective when they are highly realistic, emulating flight testing as much as possible.

The Naval Surface Warfare Center at Indian Head, MD (NSWC/IHD) has developed a facility for ground testing the Tomahawk cruise missile that strongly conforms to the Welch report's philosophy. The Functional Ground Testing (FGT) Facility tests missiles through all phases of their flight from boost through cruise to flight termination. Actual All Up Rounds (AUR) of all Tomahawk variants with inert payloads are exercised with actual operational flight software (OFS) and a real time 6 DOF simulation that provides the missile with all of the sensory data it would receive when executing its mission. This Tomahawk Missile in the Loop (TMIL) concept provides data that could otherwise be only obtained through flight test--at a cost an order of magnitude less than flight testing. FGT is not a replacement of HWIL or flight testing, but does provide an important risk reducing step by bridging the gap between the two.

This paper will describe the details of the FGT, its proven ability to reduce risk and cost on the Tomahawk program, and its potential adaptability to other missile programs.

Overview of the FGT Capability

The Tomahawk FGT capability was first implemented by General Dynamics in 1986 to test and evaluate the Tomahawk Land Attack Missile-A (TLAM-A). Resident test software was used to exercise 27 missiles using simple time and event tables. In 1990 NSWC/IHD was tasked to take over the FGT program. The Tomahawk missile has evolved considerably since then and the FGT capability at NSWC/IHD has evolved with it. The NSWC/IHD FGT now supports all Tomahawk variants and incorporates the actual operational flight software (OFS) with a real time 6 DOF simulation. To adapt to the latest Tomahawk technology, the facility includes a Digital Scene Matching Area Correlation (DSMAC) scene generator to produce images of the mission for the on-board DSMAC camera, a GPS satellite simulator to provide GPS data, and a Variable Radar Altimeter Test Set (VRATS) system to receive the missile radar signals and simulate a response of the terrain reflection. In addition, the FGT team has collaborated with NSWC/Dahlgren to provide remote "launching" capabilities using the Tomahawk Weapon Control System (WCS) at Dahlgren to test the missile at Indian Head. These improvements provide the Tomahawk program a unique test capability that provides the maximum amount of data short of conducting flight tests.

FGT Operation

Figure 1 below depicts a functional diagram of the FGT operation. The FGT starts with the power up and initialization of the missile, pre-launch alignment and execution of a launch sequence. During the boost phase of the mission all missile functions occur as in flight including rocket motor firing, thrust vector control, separation of all jettisoned items, deployment of fins, inlet duct and wings. Transition to cruise includes booster separation and start up of the turbofan cruise engine. Cruise phase exercises the missile's guidance systems including simulated Inertial Guidance, TERCOM, DSMAC and GPS. The missile navigates to a simulated target and the terminal missile functions are exercised, including the warhead detonation command.

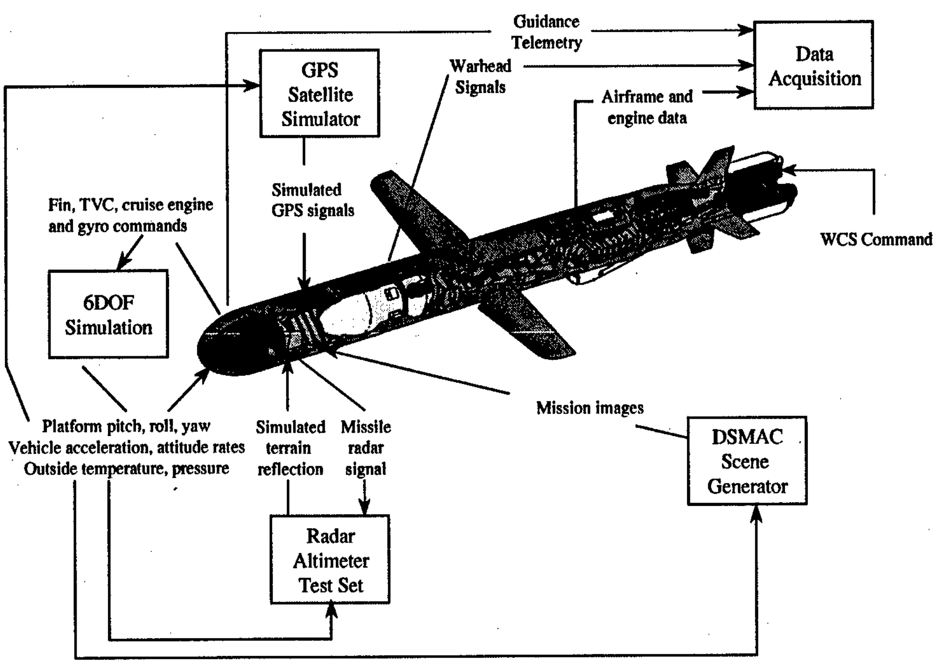

Figure 1. FGT operational block diagram

The simulated flight is initiated by the Tomahawk tactical weapon control system (WCS) at Dahlgren (or by a WCS simulator at Indian Head) which provides the intent to launch, rocket motor arm, and fire commands. Once "launched" the 6DOF simulation provides the sensor data that would be generated in an actual flight (i.e. launch platform roll, pitch, and yaw angles and rates, environmental temperature and pressure data, and missile acceleration and roll, pitch and yaw rates). This data is fed through the Portable Computer Test Unit (PCTU) to allow the missile OFS to use the simulated sensor data. The 6DOF also provides data to the DSMAC scene generator, GPS satellite simulator, and VRATS system to allow these systems to provide the missile with the remainder of its external information. The missile responds to all of these data with fin, TVC, engine throttle and gyro commands as it would in flight. Figure 2 below depicts the Tomahawk missile under test. These commands operate their respective components and are relayed back through the PCTU to the 6 DOF simulation to close the loop. All of this is done in real time and an animation of the missile in flight over the terrain is displayed to the test operator. An example of the animation is illustrated in Figure 3.

While the missile is "in-flight" the same airframe and guidance telemetry data that is collected during a flight test is recorded during an FGT. Telemetry data collected in FGT agrees well with telemetry data taken in flight tests for the same mission[3]. Telemetry data can continue to be collected even if a control system fails (so long as the proper command is issued) an advantage not available in flight testing.

In addition to airframe and guidance telemetry, visual data are also recorded using video and high-speed film. Finally, crucial information can come from the vehicle itself post-test. In flight testing, the test vehicle can be damaged after testing or unrecoverable, making failure analysis more difficult.

Although it has many technical and cost benefits, FGT is not a replacement for flight testing, and does not include all of the elements of an actual Tomahawk flight. FGT does not provide platform/missile integration testing or simulate the environment associated with flight (i.e. air loads, vibration, acceleration forces, and aerodynamic thermal effects) other than ambient conditions.

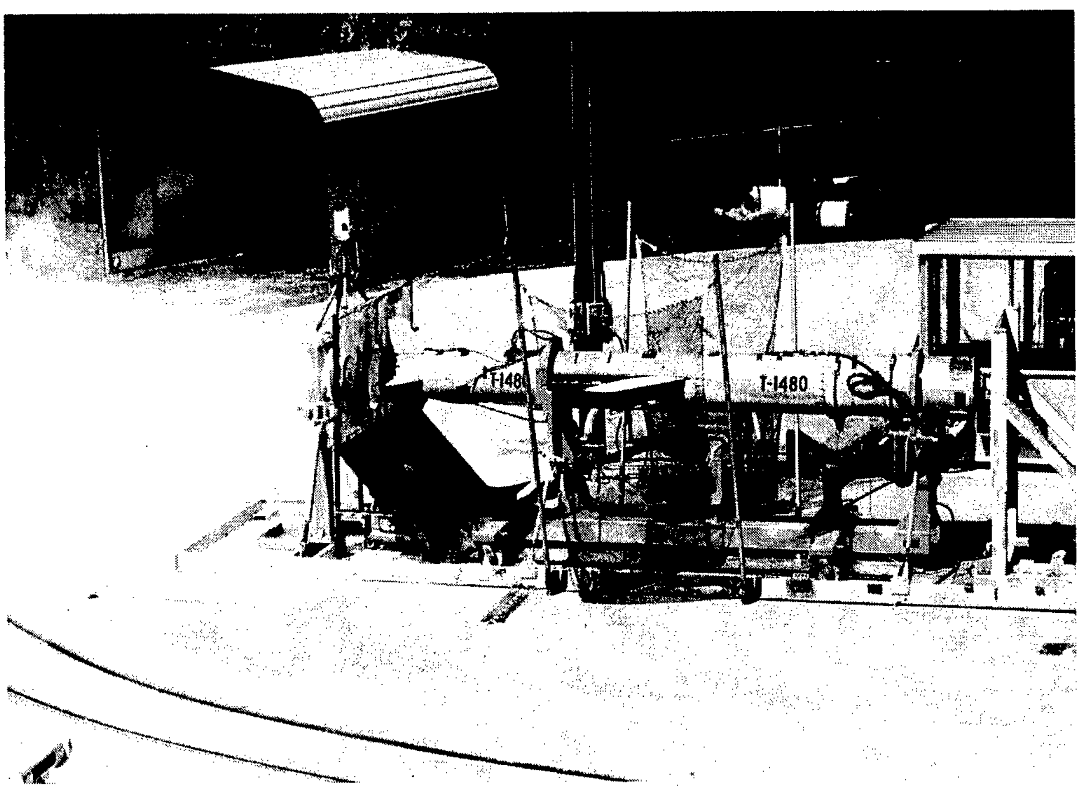

Figure 2. Tomahawk missile during Functional Ground Test.

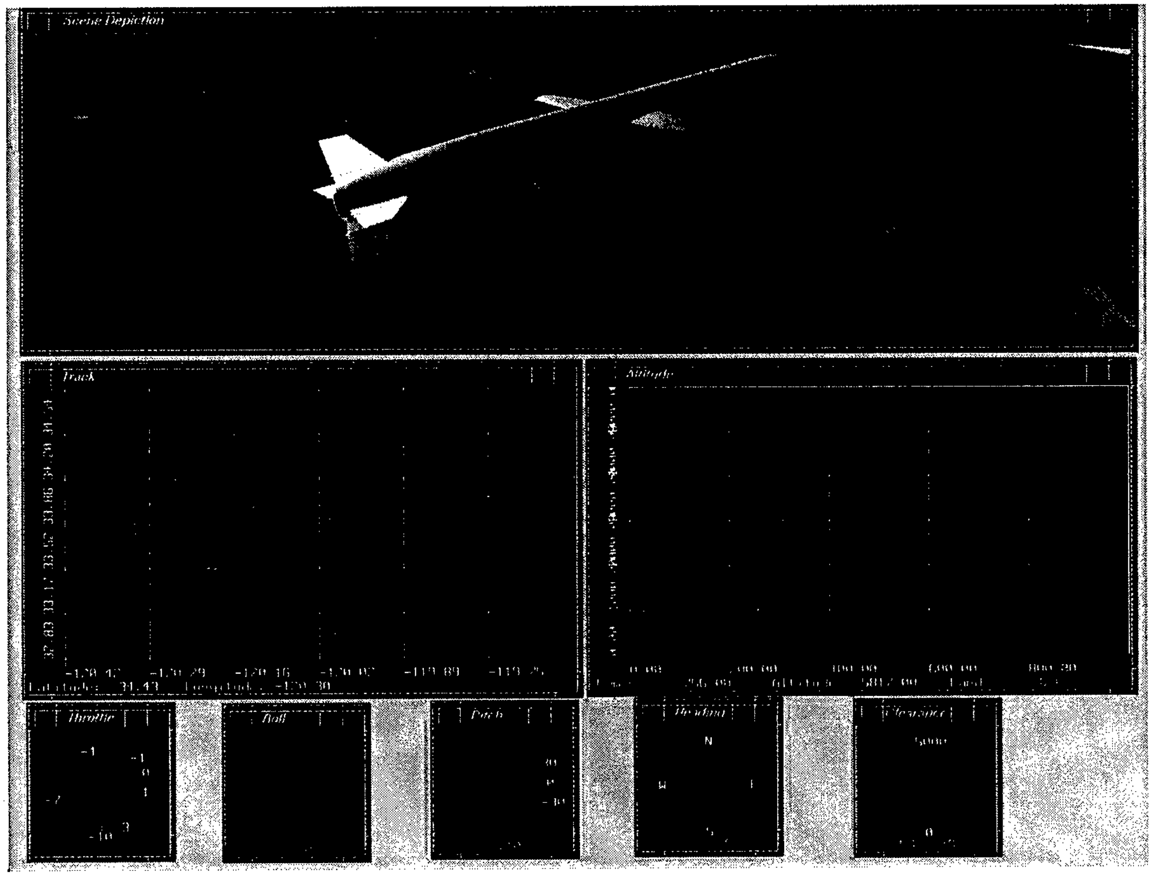

Figure 3. Sample 3-D simulation display using missile data from FGT.

Risk Reduction, Cost Savings, and Reliability Enhancement using FGT

Low cost, low risk testing such as FGT offers a means of weapon evaluation not always possible through flight testing. A role of a test program is to increase the quality and reliability of the fielded weapon. In addition, FGT plays an important role prior to flight testing, providing a check of the integrated system before actual launch.

The combination of high capability and low cost has made the FGT facility ideal for many roles in the Tomahawk program. FGT is used for Product Verification Testing (PVT) to ensure new missile quality and reliability. Also, system design changes are first investigated through FGT as part of the Engineering Change Proposal (ECP) process to reduce the risk of flight test failure due to the change. FGT is also used in the Service Life Assessment Program (SLAP) to assess the reliability of aged missiles from inventory. Finally, FGT is to be used in development testing of new Tomahawk variants such as Tactical Tomahawk to reduce flight test risk.

Risk Reduction

The FGT facility has a proven track record of reducing flight test risk. An example of FGT risk reduction capability is shown by examining flight test failures up through 1998[3] as shown in Figure 4 below.

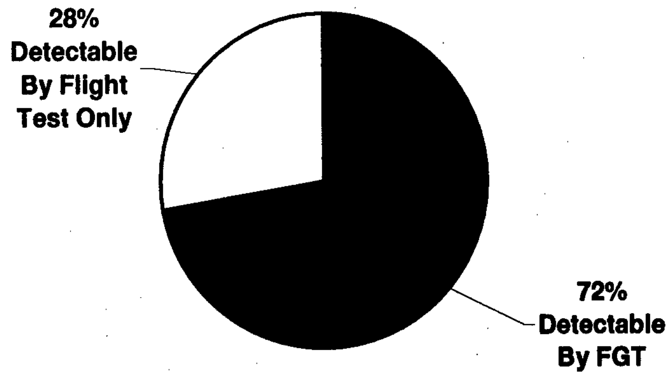

Figure 4. Percentage of Anomalies/Failures Detectable During FGT

Of the 115 failures and anomalies identified during flight tests and tactical flights 83 or 72% could have been detected by FGT. In addition, referring to figure 5, most types of anomalies/failures are detectable by ground testing. Budgetary pressures have pushed the annual number of Tomahawk flight tests from a peak of 27 in 1988 to just 8 in 1998. The ability of FGT to detect missile problems helps greatly reduce the overall program risk.

Fifty-four FGTs have been performed to date at NSWC/IHD. Examples of past FGT objectives are:

- Missile component testing such as fuel compatibility testing and testing of a new fin actuator
- Manufacturing process testing such as "flight" performance of refurbished rounds and testing of rounds manufactured at a new facility
- Collection of engineering data such as assessment of flight performance as fuel is depleted (beyond normal flight test duration) and measurement of the shock associated with pyrotechnically deployed items

A successful FGT of a missile containing a new component or manufactured through a new process reduces the risk of that component/process causing a subsequent flight test failure.

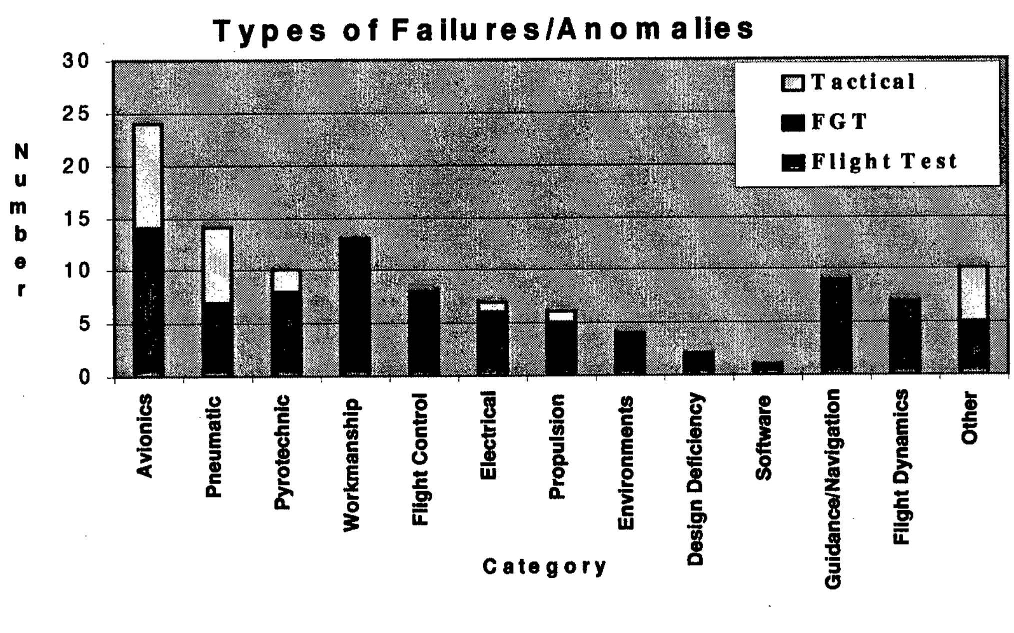

Figure 5. Breakdown of Types of Anomalies/Failures

Cost Savings

Ease and scope of data gathering is a strong advantage of FGT but its greatest advantage is its cost. The current cost estimate of FGT is ~\$60K compared with an estimated \$2M for a flight test. Of great significance, the test round itself can be refurbished and placed back into inventory, eliminating the need to "purchase" the round for testing. Since FGT uses the OFS, special test software development and maintenance are not needed, helping to keep test costs low.

A tremendous cost savings has been realized by the ability of the NSWC/IHD FGT to detect potential problems that would otherwise be found in flight test, potentially leading to flight test failures. FGT has discovered anomalies and failures caused by design deficiencies, manufacturing errors, and assembly errors such as booster separation ring failure, generator/regulator bearing failure, engine surges due to mismanufactured turbine blades, fuel leaks, and shorts caused by booster cable separation. Figure 4 shows the types of failures and anomalies that have occurred during FGT. If these failures had occurred in flight testing (i.e. if the failed missile was selected for OTL vs. FGT), the missile asset (valued at \$600K-\$1.2M) would either be destroyed/unrecoverable or would require a costly recover and refurbish operation. Cost savings based upon the failure being found during an FGT vs. an OTL are estimated at \$22M. In addition, corrective action such as additional factory tests or inspections and missile design improvements taken as a result of FGT discoveries has helped increase the quality of the missile.

One significant deficiency that was found was a booster separation ring failure. This discovery prompted the recall of ~100 deployed Block III TLAM C missiles to correct the failure mode. Missile asset cost avoidance alone for this discovery is \$60M (\$600K/missile). However, of greater significance is discovering this problem before these assets, ~10% of all of the deployed Block III TLAM C missiles, were called upon in a military exercise. The value of significantly increasing the reliability of the deployed weapon far exceeds that of the missile asset cost.

In addition to discovery of missile deficiencies, the ability of FGT to simulate flight testing allowed the Navy to eliminate flight test for Y2K investigation and use FGT instead, a \$2M cost savings.

FGT has also helped to reduce Tomahawk operational costs by exercising aged missiles which provided data to support extending the recertification interval of deployed missiles from three to five years reducing recertification costs (\$100K/missile) by 40%. Overall, it is estimated that Functional Ground Testing of Tomahawk missiles has resulted in a total cost avoidance to the Tomahawk program in excess of \$260 million.

Applicability of FGT to Other Missile Programs

The merits of a comprehensive simulation provided by FGT have been illustrated on the Tomahawk program. However, its success need not be program-specific. Adapting a FGT capability to accommodate next generation missiles which have some similar systems (i.e. GPS-aided navigation) is not difficult to envision. Other precision strike missiles such as the JASSM, JDAM, Harpoon Block II, JSOW, and SLAM ER which are now entering or have recently completed the Engineering, Manufacturing, and Development phase of their programs could also benefit from a FGT capability to meet future Follow-On Test and Evaluation requirements. Using similar technology used in the Tomahawk FGT program would make the development of a ground test capability for other weapon systems to be relatively quick and inexpensive.

Applications to Ballistic Missile Defense

The strength of FGT is the ability to not only test a missile component during a simulated mission but to test an entire missile system and associated component interactions. This end-to-end system simulation capability is precisely what is called for in the Report of the Panel on Reducing Risk in Ballistic Missile Defense Flight Test Programs. This report found that current ground testing on Ballistic Missile Defense (BMD) programs is inadequate and this testing deficiency is increasing risk on flight tests to an unacceptable level. Results of recent unsuccessful intercept attempts in several BMD programs are evidence of this conclusion.

Another interesting conclusion of the Report is that the above failures have little to do with the challenging hit-to-kill problem. Often, the supporting systems--which use well established technology--that get the kinetic kill vehicle into position to engage and intercept the ballistic missile target are the causes of the flight test failure. For example, causes of failed intercept attempts on the THAAD program have included: missile thrust vector control errors causing missile instability, divert attitude control system errors due to epoxy

contamination on a shorting pin, and tracking errors due to failure of a data umbilical cable during kill vehicle/booster separation.

Implementing a FGT capability would detect errors such as those listed above for far less that the $12M flight test cost and without the same political repercussions. Test costs are kept low in part due to the ability to recover the missile and refurbish components, particularly with BMD missiles that can cost $6M.

Conclusions

The current climate of decreasing defense budgets and evolving threats calls for advanced testing capabilities to quickly and inexpensively develop reliable, high quality weapon systems. Bypassing risk-reducing simulations and ground testing to accelerate fielding of the weapon has been shown to be an ineffective method in ballistic missile defense, ultimately costing the program more and causing delays in schedule resulting from flight test failures.

The Tomahawk FGT facility at NSWC/IHD has proven to be a highly effective element in product verification, design change investigation, and service life assessment. At far less than the cost of a flight test, the FGT facility is able to virtually "fly" a missile through all phases of its flight gathering valuable data, including data that is only otherwise available through flight test.

The FGT program has resulted in a cost avoidance to the Tomahawk program of an estimated $260M and helped to reduce flight test risk. The FGT team has proven to be able to adapt with the changing needs of the Tomahawk program and modification of the facility to accommodate other weapon programs is possible. The ultimate benefit of FGT is improving the quality and reliability of the Tomahawk, providing the warfighter with a better weapon.

[1] Rumsfeld, Donald H., et al. "Report of the Commission to Assess the Ballistic Missile Threat to the United States. Pursuant to Public Law 201, 104th Congress", July 15, 1998.

[2] Welch, Larry D., et al. "Report of the Panel on Reducing Risk in Ballistic Missile Defense Flight Test Programs", February 27, 1998.

[3] Tomahawk Cruise Missile Failure Analysis Report Library Reference Guide, PEO (CU) dated July 1994, including Incremental Change 1.

[4] Tomahawk Data Review Handbook, AUR-SES-96-004, revision F dated June 1996

[5] Kruger, Martin R., Spriggs, Michael J., and Sterling, Sherry ; "Tomahawk Functional Ground Testing", Technical Proceedings, Fleet Maintenance in the 21st Century, A Joint Symposium Sponsored by the Commander-In-Chief, U.S. Atlantic Fleet and the American Society of Naval Engineers, 22-23 October 1991.

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